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Control of Wood Stove Emissions Using Improved Secondary Combustion

Battelle Columbus Labs., OH

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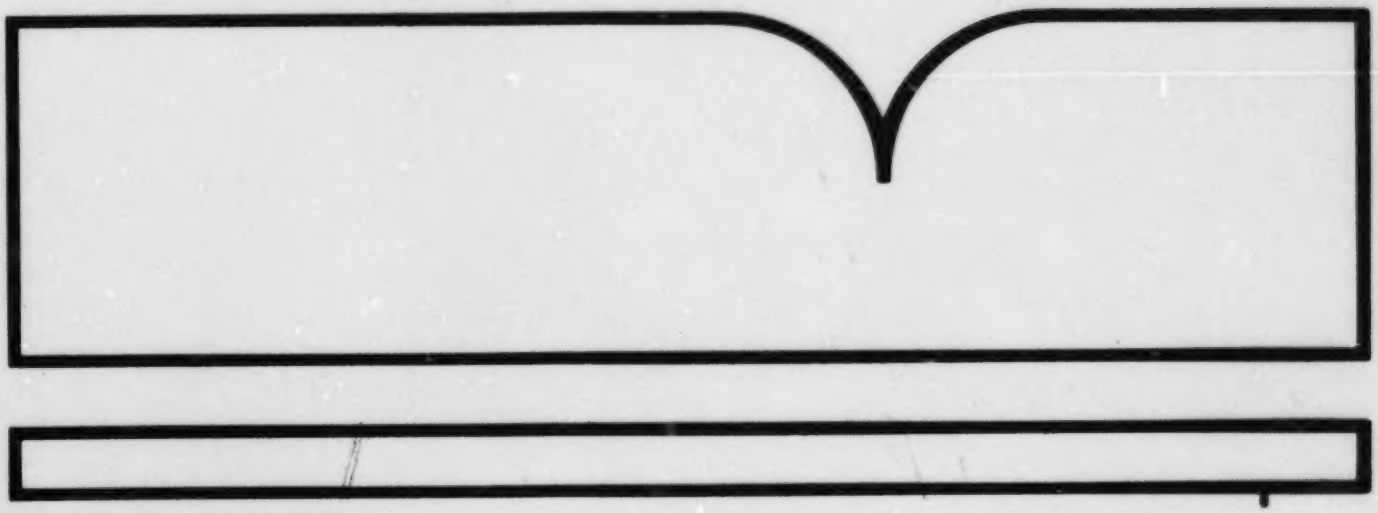

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CONTROL OF WOOD STOVE EMISSIONS USING IMPROVED SECONDARY COMBUSTION

by

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16. ABSTRACT The report gives results of the operation of two wood stoves in the laboratory with simultaneous on-line chemical analysis of the gases entering the secondary combustion zone and those leaving the stove. (NOTE: Self-initiating secondary combustion in wood stoves is encouraged by designs that introduce additional heated air and turbulence to the primary combustion products. This can be very effective in reducing CO and hydrocarbon emissions at high burning rates. At low burning rates, the effectiveness is limited by low temperatures, inadequate mixing, and thermal quenching by the primary air which bypasses the wood.) Stove modifications providing increased temperatures and improved mixing in the secondary combustion zone in a small box stove resulted in minor improvements in secondary burning. The continued burning of CO in the secondary zone was not greatly affected. In a large side-draft stove, with effective secondary burning at high burning rates, the secondary burning at low rates was not effective at any air flow distribution available to the operator.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Stoves	Stationary Sources	13A
Wood	Wood Stoves	11L
Combustion Control	Secondary Combustion	21B
Carbon Monoxide		07B
Hydrocarbons		07C

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ABSTRACT

Self-initiating secondary combustion in wood stoves is encouraged by design configurations that introduce additional heated air and turbulence to the primary combustion products. This can be very effective in reducing CO and hydrocarbon emissions at high burning rates. At low burning rates the effectiveness is limited by low temperatures, inadequate mixing, and thermal quenching by the primary air which bypasses the wood. Two stoves were operated in the laboratory with simultaneous on-line chemical analysis of the gases entering the secondary combustion zone and the gases leaving the stove. Stove modifications providing increased temperatures and improved mixing in the secondary combustion zone in a small box stove resulted in minor improvements in secondary burning. The continued burning of CO in the secondary zone was not greatly affected. In a large side-draft stove which had effective secondary burning at high burning rates, the secondary burning at low rates was not effective at any of the tested air flow distributions.

CONTENTS

Abstract iii
Figures vi
Tables vii
Acknowledgement viii

1. Introduction 1
2. Summary and Conclusions 3
   - Air tight design significance 3
   - Turbulence 3
   - Thermal effects 4
   - Large stove with preheated secondary air 4
   - Hydrocarbons compared to carbon monoxide 4
   - Advanced stove design 4
3. Experimental Program 5
   - Stoves investigated 5
   - Laboratory installation 5
   - Experimental procedures 8
4. Small Stove Tests: Effects of Modifications 13
   - Secondary air control system 13
   - External thermal insulation 18
   - Internal primary chamber insulation 19
   - Internal secondary chamber insulation 22
   - Discussion of results 23
5. Large Stove Tests: Effects of Operation Techniques 30
6. Advanced Stove Design to Optimize Secondary Combustion . . 39

References 40

FIGURES

Number		Page
1	Schematic diagram of stoves	6
2	Gas temperature profile inlet to secondary combustion zone	7
3	Wood stove gas sampling system	9
4	Stove modification A primary air distributor	15
5	Stove modification B secondary air distributor	16
6	Stove modifications D and F, internal insulation	21
7	Wood stove combustion gas temperatures	24
8	THC and CO concentrations in wood stove combustion gases	26
9	Emission factors, Nordic stove, Test 10	27
10	Defiant stove, Test 1, burning large pieces of wood	32
11	Defiant stove, Test 2, burning smaller pieces of wood	33
12	Defiant stove, Test 3, restricted primary air supply	34
13	Defiant stove, Test 4, normal primary air supply	35
14	Defiant stove, Test 5, secondary air supply closed	36
15	Defiant stove, Test 6, primary air supply closed	37

TABLES

Number		Page
1	Emission factor averages	14
2	Effects of direction of injection of controlled secondary air .	17
3	Comparison of controlled and conventional secondary air introduction	20
4	Test observations summary	29
5	Emission factor averages for different air supply control settings	31

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SECTION 1

INTRODUCTION

Increased use of wood as a residential heating fuel has resulted from the rising prices of other fuels and public skepticism about the reliability of normal fuel supplies. Government agencies, equipment manufacturers, and many environmentalists are supporting the use of wood as an alternate fuel. With the increase is also the widespread impression that wood burning is environmentally clean. Unfortunately, the technology characterizing the objectionable emissions from wood stoves is limited, and few experiments to try to effectively reduce emissions have been done. In many instances the residential stove manufacturers and operators are adopting stove designs and operating practices that increase emissions. This accentuates the environmental significance of the increasing use of wood as a residential heating fuel.

As a means of reducing objectionable emissions from residential wood stoves, five methods have been identified:

(1) Preventing or reducing emissions formed in the fuel magazine within the stove.
(2) Preventing or reducing emissions formed in the primary combustion zone.
(3) Destroying emissions within the primary combustion zone.
(4) Destroying emissions in a secondary combustion zone.
(5) Adding systems or devices for emission reduction.

Of the five methods, the first three can be accomplished by burning well seasoned wood at a relatively high rate. The recently introduced stoves with catalytic afterburners employ Method 5, so it is not discussed in this report. The application of Method 4 is the focus of this study. The purpose of the research was to investigate the effects of various modifications of commercial stoves as a means of improving the effectiveness of secondary combustion.

Secondary combustion is the combustion of fuel materials that are not completely burned in the primary combustion zone, that is in the immediate vicinity of the wood. These materials can result from quenching the primary combustion products or from pyrolysis of wood without complete combustion in the primary combustion zone. Secondary combustion can be achieved by mixing the gases from the wood and from the primary combustion with suitable oxygen at a temperature sufficient to ignite the mixture or sustain burning. In some situations secondary combustion is an extension or continuation of primary combustion and specific secondary ignition may not be required. In

some stoves secondary combustion takes place directly above the burning wood. In other stoves, the secondary zone is separated from the primary zone by a baffle or barrier; the primary and secondary air are supplied at different locations. For secondary combustion to take place the gas composition must be within the flammability limits of the gases. Adding secondary air can sometimes dilute the combustion gases below these limits or cool the mixture below ignition temperatures.

In actual practice secondary combustion is hindered by:

- Limited mixing rate and turbulence are due to low air velocities available within natural draft stoves
- Low temperatures in the secondary zone due to excess air and wall quenching
- Uncontrolled rate of secondary air supply

As a result, in many conventional stoves secondary combustion is often not sustained for any significant length of time. Just after a charge of new wood has been added, the temperature of the secondary air and the combustion products may be too low to inititate or maintain secondary combustion. In mid-period burning the gases from pyrolysis tend to be hotter and contain more combustible matter, thus satisfying the conditions for continued burning. Later in the burning cycle gas evolution is reduced as the wood becomes char and there may be insufficient combustible gas to sustain secondary burning.

SECTION 2

SUMMARY AND CONCLUSIONS

This program has demonstrated that secondary or continued combustion supported by an independent secondary air supply is very difficult to attain at low burning rates in wood stoves. An almost universal characteristic of wood stoves at low burning rates is the abundance of excess air in the combustion products leaving the primary combustion zone. At these low burning rates, the pyrolysis and immediate partial burning of the wood results in some unburned fuel gases (CO and hydrocarbons), which leave the wood with the combustion products. The combustible concentration range of these fuel gases is limited by the low temperature, and limited further by the concentration of inert compounds (residual nitrogen and reaction products of completed burning). The requirements of a minimum temperature and an acceptable mixture of fuel, air, and the diluent inerts are seldom met.

AIR TIGHT DESIGN SIGNIFICANCE

A conventional baffled box stove was first operated as purchased and subsequently operated with modifications intended to improve the effectiveness of secondary combustion. Dispersed and uncontrolled secondary air introduction (through leaks) resulted in stove emission factors that were at least as low as those obtained with any of several restricted and controlled secondary air introduction systems. However, the burning rate was not easily controlled until the stove was sealed to be "airtight". The reduction in emission factors obtained within the secondary combustion chamber by the controlled introduction of secondary air was generally greater than the reduction obtained in the same upper chamber of the stove with the uncontrolled, secondary air supply. These observations are consistent with the generally recognized characteristics of airtight stoves.

TURBULENCE

A mild degree of turbulence and mixing was introduced into the inlet of the secondary combustion zone by injecting secondary air into the stove through small jets. Only when the jets were directed counter to the primary flue gas stream was there evidence of turbulence-induced continued combustion. At best, the emission factors for CO and hydrocarbons were reduced 40 percent.

THERMAL EFFECTS

Thermal insulation was applied to the small box stove in several places to attempt to increase significantly the temperature of the combustion gases at the point where secondary air was supplied. Reductions of up to 46 percent of the emission factors of CO and hydrocarbons were then obtained in the secondary combustion. Extensive insulation was apparently not sufficient to maintain the gases at high enough temperatures to complete the combustion process during low rates of burning. Only when the burning rate was increased appreciably and gas temperatures in the secondary combustion chamber were above 425 C were more significant reductions in emission factors observed.

LARGE STOVE WITH PREHEATED SECONDARY AIR

The same instrumentation and operating procedures were applied to a larger stove with preheated secondary air introduced through jets into the primary combustion products. Results similar to the small box stove were observed at low burning rates, with correspondingly high concentrations of oxygen in the gas leaving the primary combustion zone. Averaged over complete burns, the reduction of CO and hydrocarbon emission factors was generally less than 50 percent, and the effects of secondary air flow rate were not significant. During short periods early in some test burns, gas temperatures exceeded 425 C, and reductions in emission factors exceeding 50 percent were observed.

HYDROCARBONS COMPARED TO CARBON MONOXIDE

In all conditions of operation, carbon monoxide continued to oxidize slowly during the gas transit through the secondary combustion zone, whether the hydrocarbons were oxidized significantly or not. Although the lower temperatures may have impeded the oxidation of CO, it was not completely quenched. Secondary or continued combustion of the hydrocarbons was less evident, and more erratic than the CO combustion. The technique used for analysis of hydrocarbons (flame ionization detection) is known to be inexact for the many gases released from wood, but this possible discrepancy is not considered to be significant.

ADVANCED STOVE DESIGN

A newly marketed advanced stove design which optimizes secondary combustion was found by TVA to be very effective in reducing emissions at medium and high burning rates. The secondary combustion in that stove was found to be ineffective at low burning rates. This is similar to the observations from this program.

SECTION 3

EXPERIMENTAL PROGRAM

STOVES INVESTIGATED

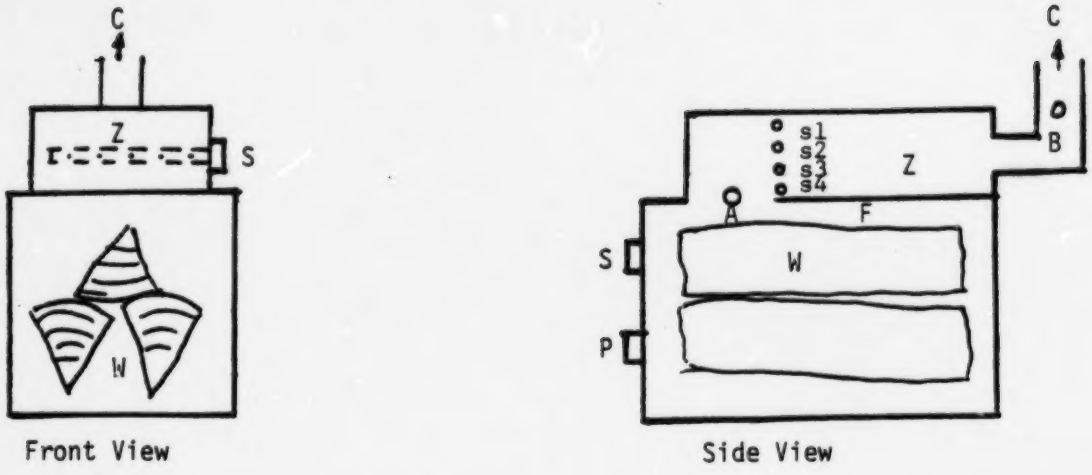
A Nordic small box, or S-draft stove and a larger side-draft Defiant stove were used in this study. Both were made in this country. The box stove has a rectangular secondary combustion chamber above the horizontal baffle. This chamber was easily modified for combustion studies. Both primary and secondary air were admitted through adjustable ports in the door--one high port for secondary air and two lower ports for primary air. The primary combustion chamber volume was 0.042 m^3. Figure 1 shows schematic diagrams of both stoves.

The larger side-draft, or cross flow, stove was used to demonstrate efficient secondary burning. Both primary air and secondary air are distributed through existing internal ducts; thus the air is heated before it is released into the stove through small holes or tuyeres. The internal ducting is designed by the manufacturer to direct primary air horizontal to the base of the wood; this effectively reduces or eliminates primary air bypassing the wood in the primary combustion zone. The secondary air is also introduced by the tuyeres in a cross flow pattern. This method promotes mixing and improves distribution of the heated secondary air. The primary combustion chamber volume is 0.126 m^3.

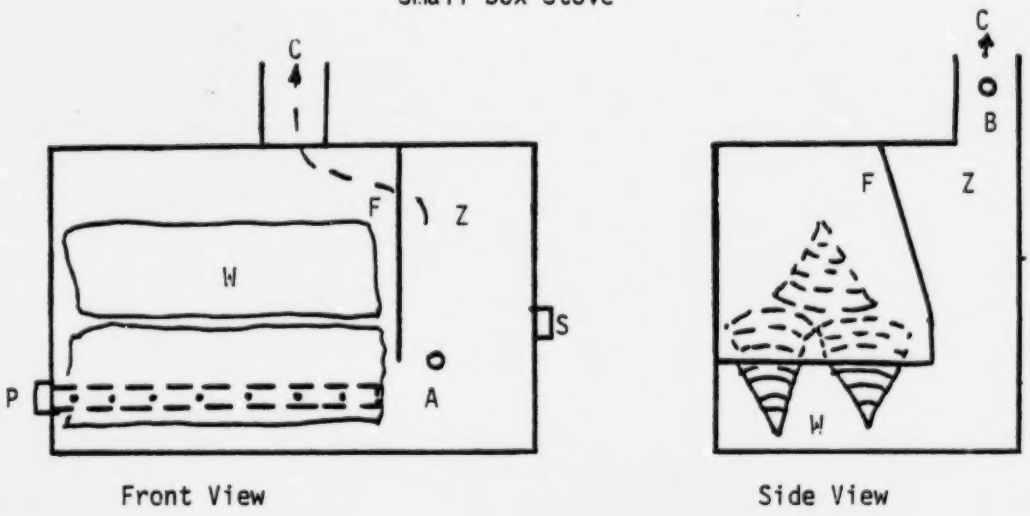
LABORATORY INSTALLATION

The stoves and their insulated stacks were mounted on a platform that permitted weight loss (burning rate) measurements during operation. Both stoves were equipped with shielded aspirated thermocouples at the inlet and outlet of the secondary combustion zone to measure temperature. By forming the thermocouple shield into a rake type of sampling probe extending across the chamber, representative gas samples and temperatures could be obtained through the same probe. This increased the sensitivity of monitoring the secondary burning.

To select the placement of the rake probe in the box stove, a temperature profile of the combustion gas entering the secondary chamber was taken by traversing the chamber with a thermocouple. The graphical results for the four vertical levels and ten horizontal points at the entrance to the secondary chamber are shown in Figure 2. Based on this profile, sampling position No. 3 was chosen. The probe was designed with six equally spaced horizontal sampling holes. The rake probe in the side-draft stove was



Small Box Stove



Large Side-Draft Stove

Legend

Alternative secondary air inlets

- s1 upper inlet
- s2 No. 2 inlet
- s3 No. 3 inlet
- s4 Bottom inlet

- P primary air inlet
- S secondary air inlet
- C outlet to chimney
- F baffle
- W wood
- A primary combustion gas sample
- B secondary combustion gas sample
- Z secondary combustion zone

Figure 1. Schematic diagram of stoves.

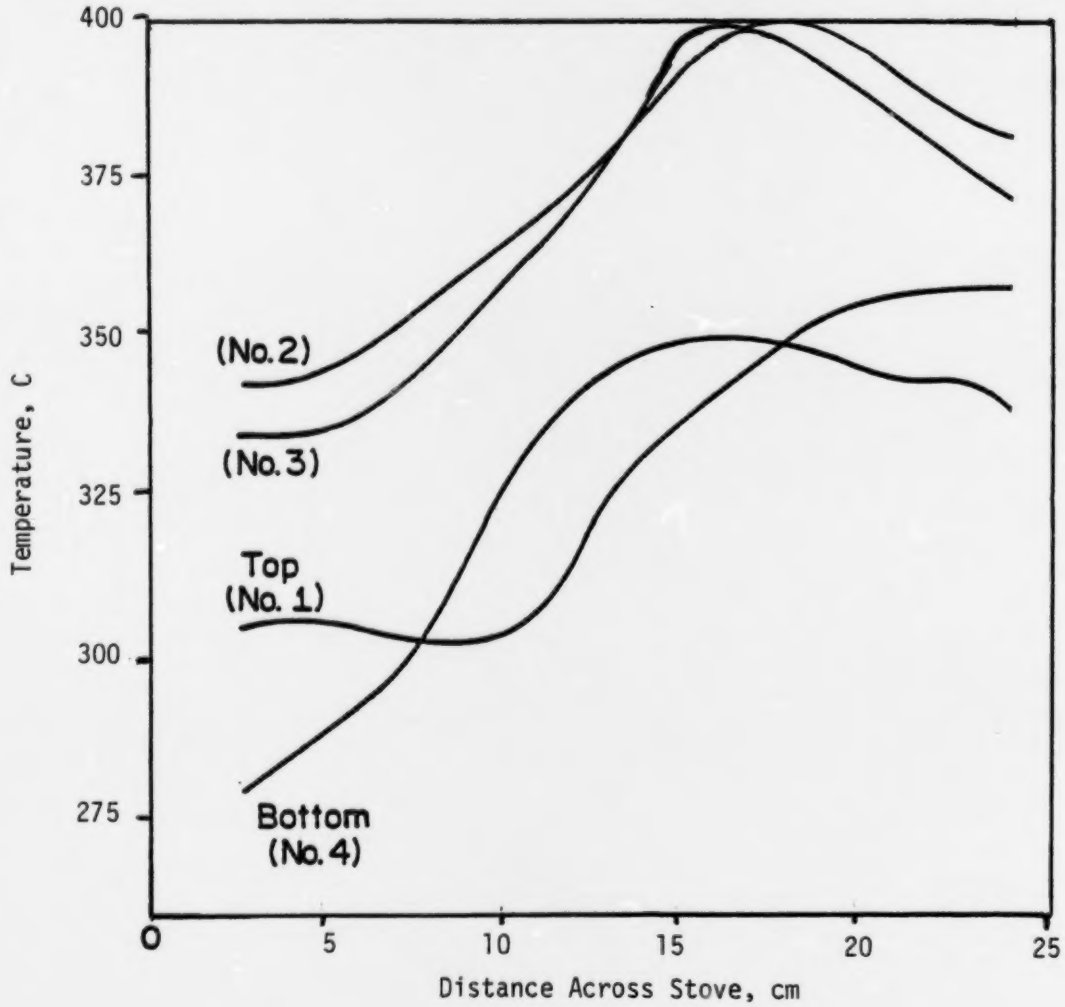


Figure 2. Gas temperature profile inlet to secondary combustion zone.

installed just downstream of the vertical baffle, under which the primary combustion products pass as they leave the wood. This is just upstream of the secondary air tuyeres. The stack sampling probes, using the same probe design, were installed in the stove pipe leaving each stove just downstream of where the flue gas left the stove. Comparison of gas analyses from these two locations in the stove provided a measurement of burning between the locations, i.e., in the secondary chamber.

Gas sampling lines were installed, and two pumps to draw out the gases were installed adjacent to the stoves. An insulated glass wool filter trap was fitted immediately before the pump inlet to prevent pump damage. One flexible line from each pump extended to the instrument room where the gas compositions were continuously monitored. The gas sample lines, pumps, and flexible lines were maintained at 204 C by individual temperature controllers. Temperatures were also manually monitored by thermocouples with a digital readout.

Inside the instrument room, the gas flow from each line was split into two lines; one heated line led to a heated Total Hydrocarbon Analyzer (THC) and the other led into a cooling/trapping system, which in turn led to inorganic gas analyzers. A schematic of the overall sampling system along with the data acquisition and data reduction system interfaces is shown in Figure 3. This system represents a highly effective method for sampling and analysis of wood stove emissions. The system was used for a large number of tests with only minor problems. The possibility of sample line plugging was eliminated by regularly changing the glass wool traps and keeping ice in the gas cooling system.

The computer program for data reduction developed by Battelle provided continuous one minute parameter checks and emission calculations. All data were stored in engineering terms for subsequent computer graphic presentations.

EXPERIMENTAL PROCEDURES

A total of 32 test burns were performed in the box stove. The first ten were "background tests" to check supporting equipment and determine operating characteristics. The reamaining 22 burns included six "baseline" tests. These six established typical and also some atypical characteristics of the unmodified stove. An additional 16 tests were performed to examine the effect of various modifications on the stove flue gas emissions. Six tests were also conducted in a large-side draft stove to demonstrate effects of secondary air control in a large stove.

The wood for these tests was all triangular split, seasoned white oak. Two different lots were used; one contained approximately 10 percent moisture and the second contained approximately 18 percent moisture (as determined by average weight loss after drying in a 105 C laboratory oven). In each case the appropriate moisture value was entered in the computer data reduction program.

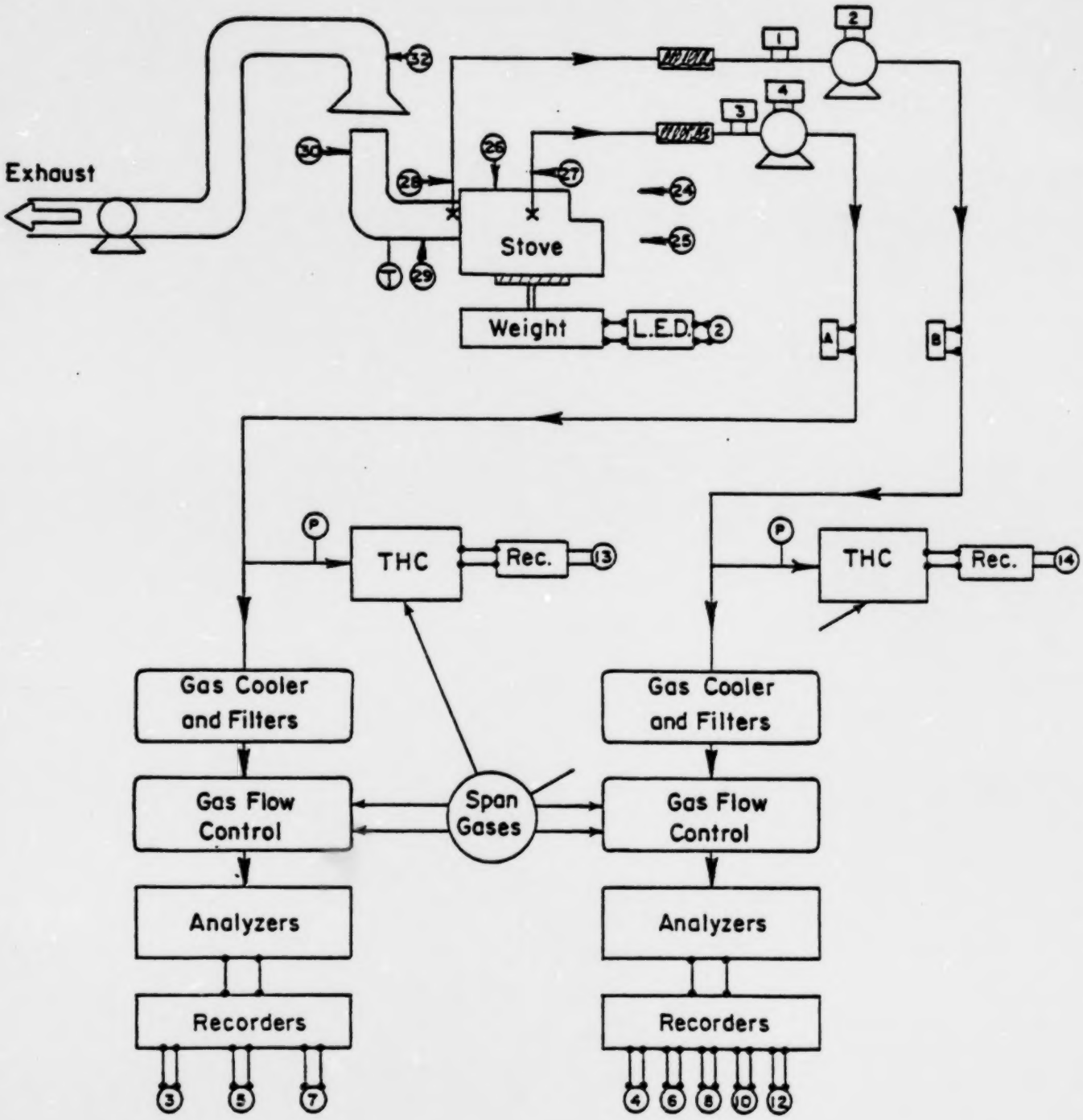


Figure 3. Wood stove gas sampling system.

LEGEND FOR FIGURE 3

FOR WOOD STOVE SAMPLING SYSTEM

Monitored Parameters (File Numbers)

(2) Weight
(3) Primary O_2 (percent)
(4) Secondary O_2 (percent)
(5) Primary CO_2 (percent)
(6) Secondary CO_2 (percent)
(7) Primary CO (percent)
(8) Secondary CO (percent)
(10) Secondary SO_2 (ppm)
(12) Secondary NO_x (ppm)
(13) Primary THC (ppm/CH_4)
(14) Secondary THC (ppm/CH_4)

Thermocouples
(24) Room Temperature
(25) Secondary Air Temperature
(26) Stove Metal Temperature
(27) Primary Chamber Outlet Temperature
(28) Secondary Chamber Outlet Temperature
(29) Stove Outlet Temperature
(30) Stack Gas Temperature
(32) Dilution Stack Temperature

(P) THC Sample Pressure Gauge
(T) Stack Thermometer

Temperature Controllers/LED Readouts
[1] Secondary Gas Sample Line
[2] Secondary Gas Pump Heater
[3] Primary Gas Sample Line
[4] Primary Gas Pump Heater
[A] Primary Gas Sample Line
[B] Secondary Gas Sample Line
Glass Wool Traps for Particulate
Gas Flows
Pumps
Electrical Connections

Before the tests began, all instruments were calibrated for zero and span. A fire was built in the stove and allowed to burn while the sample lines and pumps were being heated. The computer program was initiated by entering background information such as wood charge weight, moisture content, and type; scan interval; barometric pressure; and monitoring instrument identifications.

After the initial charge of wood had burned to glowing coals, the sample pumps were started and the sample flow rates were adjusted to flush and condition the system. The data acquisition system was then programmed to initiate sampling at a set time. Approximately 2 minutes prior to test initiation, the balance was zeroed and all flow rates and line temperatures were checked. At exactly 60 seconds prior to initiation, the stove door was opened and the preweighed charge of wood was placed in the stove. The wood was placed in a position such that two pieces were side by side with the "interior point" of the split facing down into the coals. The third piece was placed on top of these two pieces with the bark face down (See Figure 1).

The door was closed and the primary air supply was fully opened. The data processor began sampling at the preset time while the operator monitored the stack gas temperature via a digital readout from the secondary combustion outlet thermocouple. When this temperature reached 200 C, the primary air supply was adjusted to the test design conditions. This procedure assured that combustion had been initiated without opening the door to check the fire. Usually the stack temperature reached 200 C in 2 to 3 minutes, but in a few tests on the small stove 10 minutes was required. In the event of continued low stack temperaturs or serious equipment failure, the data acquisition was stopped and the test was repeated using a new charge of wood.

This method provided a generally reliable single-batch test procedure with no in-test adjustments or wood additions; however, it did present one significant problem. The design of the computer program required that the total time for the test be entered into the pretest program. This time had to be estimated by the operator, and usually only 2 to 3 percent of the wood charge remained at the completion of the test. Occasionally during poor or slow burn conditions, the remaining weight was higher; therefore, the cycle was not complete. This early termination eliminated only the lowest burning rate and lowest emission level of the cycle. No attempt has been made to adjust any of the calculated average values for this discrepancy.

This program focused on the low burning rates that prevail in most home heating applications. In this situation, high and varied values of excess air are encountered. The percentage volume concentrations of carbon monoxide (CO) and total hydrocarbons (THC) in the flue gas are depressed by this excess air, leading to the superficial view that they are less significant. In processing our emission data, the instantaneous mass rate of CO and THC emissions was calculated relative to the instantaneous mass rate of dry wood burning. This ratio is reported as the emission factor. The rate of wood burning was calculated each minute as the rate of stove weight loss over a three minute period corrected for wood moisture content. This calculation assumes that moisture release and true fuel consumption remain proportional

through the burning. Because the moisture content of most of the fuel was very low (10 percent), this error is not considered significant.

At the low rates of wood burning used in this program, the burning of large splits of wood is inherently variable as the burning process moves thru the pieces of wood. Small variations both in the wood and in the local burning become significant. The resulting emission factor are thus considered to be much less reproducible in repeat tests than when higher burning rates are employed.

The hydrocarbon rates were obtained with a flame ionization detector calibrated assuming that all hydrocarbons were as methane. The true emissions would be actually higher, because all hydrocarbons did not reach the instrument, and all those that did were not uniformly measured. The numbers are considered to be representative of true total hydrocarbon emissions, and suitable for comparisons.

SECTION 4

SMALL STOVE TESTS: EFFECTS OF MODIFICATIONS

Table 1 presents the averaged emission factors calculated for the various modes of stove operation. The background tests on the small box stove indicated that air distribution within the stove was minimally controlled by the existing air regulators on the stove door. As a result, modification A was made as shown in Figure 4. A diverter plate was installed on the stove door to direct the air from the lower ports downward into the primary combustion zone, and air from the upper port upward toward the secondary combustion zone. This plate was used in all reported tests. Although the stove was described by the manufacturer as "Air Tight", it was discovered that the total air flow could not be controlled due to excessive air leakage. As a result, after some testing all of the seams and joints of the stove were sealed with furnace cement. This provided a significant amount of control in the total quantity of air supplied but not in the internal distribution of the air. Modification A in Table 1 refers to the unsealed stovebody. In Tests 5 and 6 the internal baffle bypass was left open and the secondary air vent in the door was closed. Thus all secondary air was supplied by leakage. This is identified by L on the table.

SECONDARY AIR CONTROL SYSTEM

After the small box stove was modified by sealing all joints and cracks, it was modified further by installing a secondary air distributor in the combustion gas inlet to the secondary zone. The secondary air distributor consisted of a 1/2-inch stainless steel tube with equally spaced perforations along a single line. An air flow monitoring orifice was positioned in the air supply line leading to this distributor. A needle valve controlled air flow into the secondary combustion zone and the direction of air injection was controlled by rotating the tube. This is modification B shown in Figure 5.

During low burning rate, the effect of the direction of secondary air injection was observed while maintaining a constant secondary air flow of 40 g/hr. The primary air system was operated normally, but the conventional secondary air inlet in the door was shut. The air diverter plate was in place inside the stove door to more effectively distribute the primary air. For these tests, compressed air was used for secondary air supply to permit accurate measurement and control.

The results of these tests for four injection directions are shown in Table 2. In this case "out" is the horizontal direction into the gas flow, "down" is the vertical direction into the gas flow, "up" is vertical

TABLE 1. EMISSION FACTOR AVERAGES

Test No.	Wood Burn Rate, kg/hr	Modifications to Stove++	Average Emission Factors, g/kg of Wood Burned			
			Carbon Monoxide		Total Hydrocarbons	
			Primary Chamber	Secondary Chamber	Primary Chamber	Secondary Chamber
1	3.5*	A	77	58	10	11
2	2.6*	A	ND+	14	7	15
3	3.0	A	76	35	6	6
4	2.7*	A	104	61	18	23
5	2.9*	AL	63	45	3	4
6	2.8	AL	90	53	13	21
7	1.9	B	101	75	16	14
8	2.5	B	253	75	61	68
9	1.8	B	224	156	76	47
10	2.7	B	100	64	31	18
11	1.6	C	172	140	36	44
12	2.3	C	143	114	43	43
13	2.8	BC	157*	89	30	30
15	2.9	CD	105	83	24	37
16	2.0	CD	84	45	17	19
17	1.4	BCD	108	83	23	25
18	2.0*	BCDS	205	89	25	26
19	2.0	CDS	140	126	33	43
20	2.6	F	85	65	24	17
21	1.5	F	130	96	45	36

*Averages modified by exclusion of readings considered erroneous.
+ND = Not determined.
++Described in text as follows:

- A Unsealed stove with appreciable air infiltration. Diverter plate on inner side of firing door.
- L Internal bypass open, secondary air vent in door closed.
- B Secondary air supplied through tube at entrance to secondary combustion chamber.
- C Secondary chamber insulated by exterior ceramic wool.
- D Primary chamber walls insulated with interior ceramic wool. Firebricks installed on hearth.
- S Small sizes of fuel wood pieces used.
- F Internal firebrick used in secondary combustion chamber.

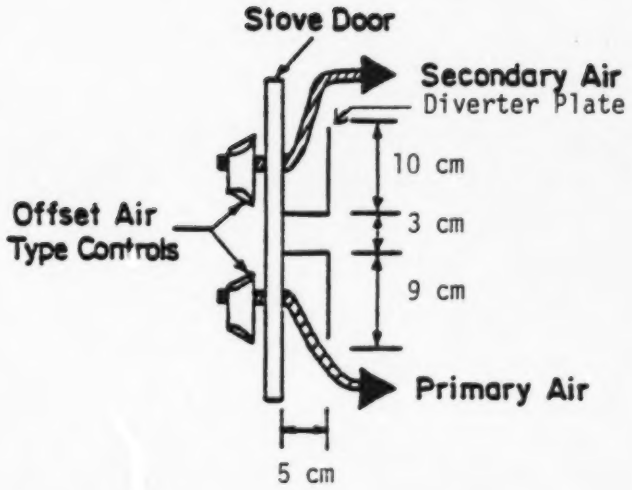


Figure 4. Stove modification A primary air distributor.

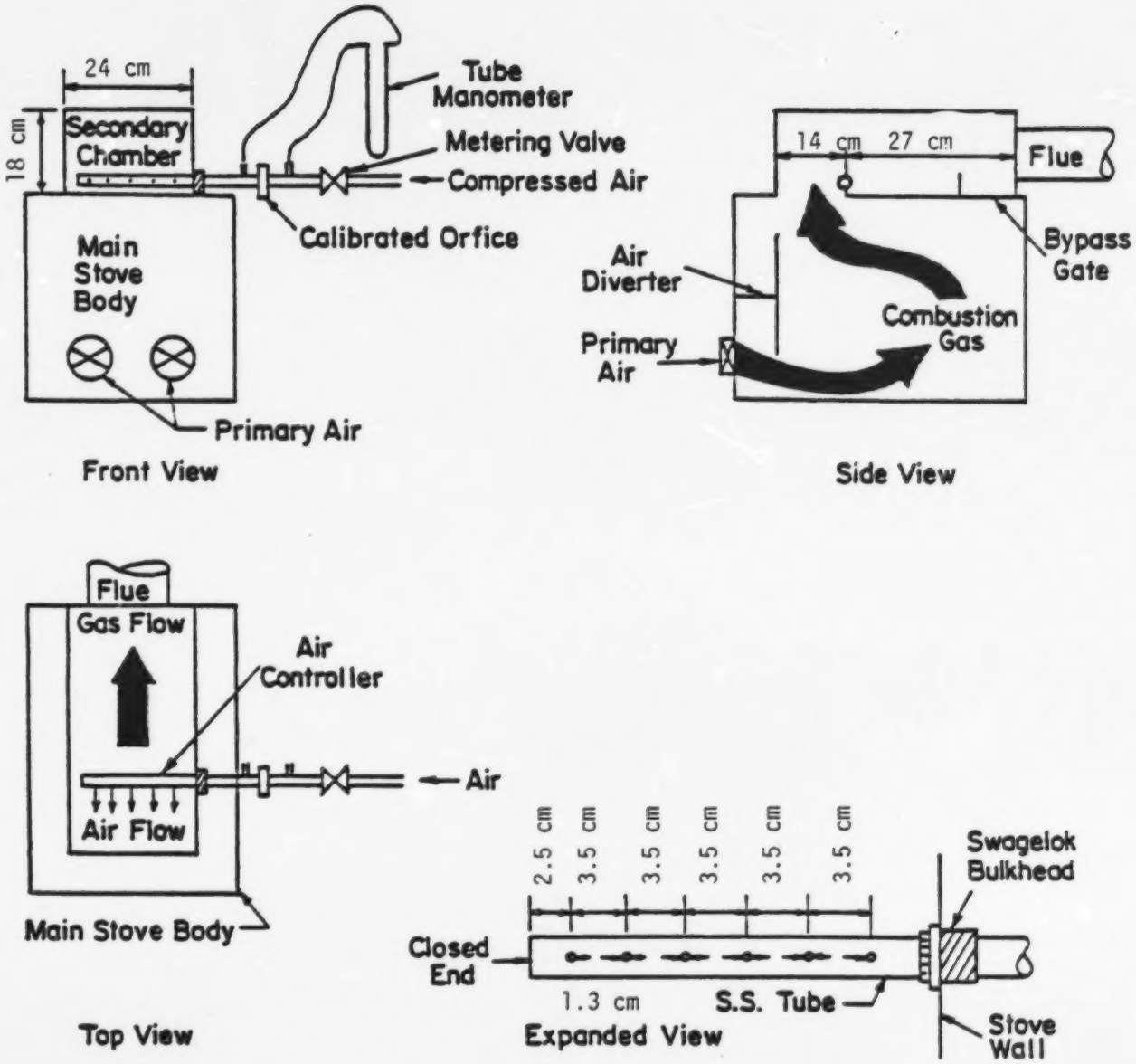
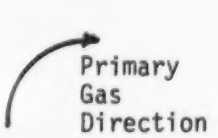


Figure 5. Stove modification B secondary air distributor.

TABLE 2. EFFECTS OF DIRECTION OF INJECTION OF CONTROLLED SECONDARY AIR

Gas Component	Direction of Injection of Secondary Air			
	In	Up	Down	Out*
				
O_2, percent	18.5	18.8	19.0	19.0 → 15.0
CO_2, percent, approx.	2.7	2.6	2.5	2.5 → 4.1
CO, percent	4	4	4	4 → 2
THC, ppm	2700	3400	3400	3200 → 1000

* The composition changed noticeably within a minute with this air injection direction with no evident change in primary combustion. Comparable changes were not observed with air injection initiated in the other directions.

direction towards the top of the stove, and "in" is direction of flow into the flue pipe. These direction vectors are identified on Table 2.

The results show that introducing the secondary air was most effective in the "out" direction, counter to the flow of the incoming combustion gas. This is the only direction of the four that caused a change in gas composition (as shown on Table 2). The controlled secondary air constituted less than 1 percent of the total air supply. Since sufficient oxygen was always available, the effects of this air injection were primarily associated with increased mixing. The distribution pipe still introduced thermal quenching because it heated the secondary air with heat from the primary combustion products.

Two monitored burns were conducted (Tests 7 and 8) using the controlled secondary air distributor in the counter flow orientation. The results were very steady burns (uniform stack temperature 200 to 260 C) and moderate to low emissions factors and excess air levels. Then, two more burns were conducted leaving the air distributor in the same orientation and increasing the air supply (Tests 9 and 10). The air volume was increased 1.7 and 1.4 times, respectively.

During these four tests the temperature of the gas stream entering the secondary burning zone was generally below 260 C except during the latter portion of Test No. 7, when sustained higher temperatures were attained. These tests indicated that the localized secondary air supplied by the distributor did not reduce emission factors as compared to the leaky stove body. In both arrangements the CO apparently continued to burn in the secondary combustion zone. The hydrocarbon emission factors were more erratic, although reductions were observed using controlled secondary air. The low mass rate of secondary air supply avoided further gas dilution and thermal quenching, but the added mixing of the gas stream was apparently insufficient to overcome the low temperature of the gas mixture.

EXTERNAL THERMAL INSULATION

The results of previous tests by Allen and Cooke (1) and Poirot and Sanborn (2) indicated that the temperatures of both the combustion air and the burning zone are important for improved combustion. A recent paper by Thornton et al (3) examined the pyrolysis and combustion of model compounds and wood gas to identify the effect of various parameters on the processes. The results indicated that a temperature of 1100 to 1200 C is the minimum required for complete combustion (defined as <3 percent of input carbon as CO and <0.5 percent as C_1 and C_3 organics). In this program, this temperature regime was never really attained. The data from Poirot and Sanborn's test show that secondary zone temperatures rarely exceed 425 C even when the secondary air is preheated. In a previous Battelle program (1), extensive secondary burning was observed when gas temperatures were above 425 C.

The secondary combustion chamber of the box stove was insulated externally to raise the temperature of the secondary combustion zone. This is referred to as modification C. For these tests, ceramic wool was

wrapped and taped around the outside of the chamber. In Tests 11 and 12, the stove was run with high levels of excess air (both primary and secondary). Total excess air ranged between 400 and 1000 percent with wood burn rates between 1.6 and 2.3 kg per hour. In both tests, there was minimal difference between emission factors for CO and THC from the primary and secondary zones. In both tests, gas temperatures in either combustion zone rarely exceeded 260 C. In Test 12, the stack temperature did exceed 260 C once with a corresponding lower secondary zone emission factor for CO and THC. This occurred approximately 33 minutes into the test. Secondary CO was between 46 and 59 g/kg of wood, secondary THC wa between 12 and 13 g/kg of wood, while primary CO was between 57 and 62 g/kg of wood and primary THC was between 15 and 16 g/kg of wood. These numbers suggest that some minimal secondary combustion might have taken place when temperatures exceeded 260 C, but it was not sustained. The stack gas temperature did drop back to 175 to 230 C.

An additional test (Test 13) included the same insulated secondary chamber, but with the controlled and directed secondary air injection. Compressed air flowed into the secondary chamber at approximately 45 g/hr (20 C) through the distributor directly above the primary zone inlet. In Test 13, the burning was very stable. The average combustion gas temperature entering the secondary zone was 259 C, with a high temperature of 297 C. Table 3 compares the test results for the insulated chamber with conventional and controlled secondary air. The average O_2 in the primary chamber effluent was slightly lower while the average CO_2 was higher. Similarly, the secondary effluent showed lower O_2 with higher CO_2. The THC emission factors appeared lower (<50 g/kg of wood) in the graphic presentation, but the average concentrations for CO (percent) and THC (ppm) showed little difference and actually were slightly higher. The results indicated that the primary combustion may have improved slightly, but there was little evidence of improved secondary combustion of the hydrocarbons.

INTERNAL PRIMARY CHAMBER INSULATION

The next tests were conducted using ceramic wool for interior insulation of the primary combustion chamber walls and using ceramic firebrick on the stove hearth. This modification (D) is shown in Figure 6. The idea was that the insulation would increase the gas temperatures by reducing heat loss to the stove walls, and that the firebrick would raise the fire closer to the secondary combustion zone. The firebricks were arranged so that the primary air flowed between them and approached the wood in a simulated updraft mode. In Tests 15 and 16 the secondary air was directed into the secondary chamber inlet through the normal door opening. High excess air (1000 to 2000 percent) resulted from operation in this mode. This modification took a significantly longer time than the other tests to reach a stack temperature of 200 C. After about 17 minutes, the stack temperature finally reached 200 C and even climbed as high as 250 C; however, the gases entering the secondary zone showed evidence of quenching from the high excess air, even though the secondary flow was only about 1/6 of the primary air flow. No reductions in hydrocarbon emissions were observed, although CO reductions were again observed.

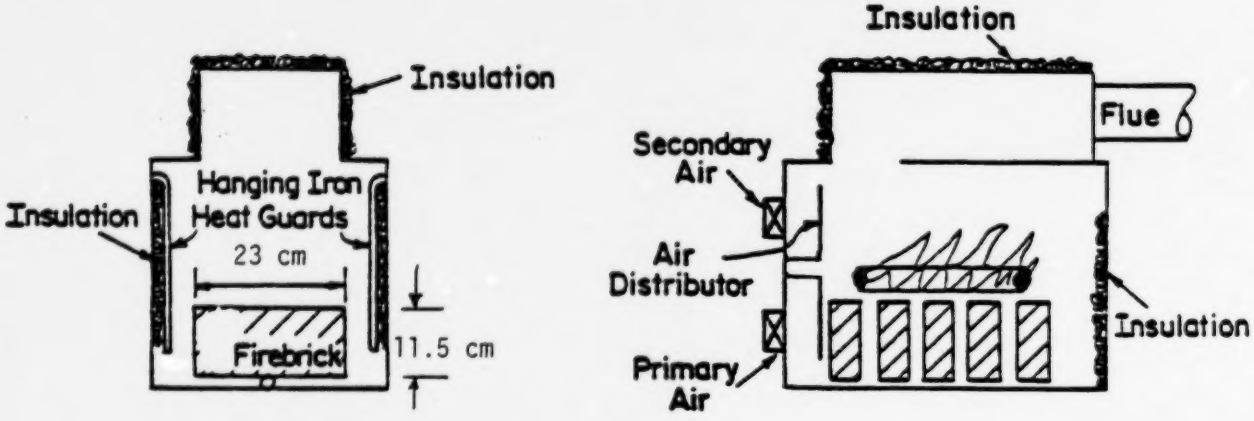
TABLE 3. COMPARISON OF CONTROLLED AND CONVENTIONAL SECONDARY AIR INTRODUCTION

	Conventional Air (Test 12)		Controlled Air (Test 13)	
	Primary	Secondary	Primary	Secondary
O_2 (percent)	17.7	18.1	16.1	17.2
CO_2 (percent)	3.4	3.2	4.2	4.0
CO (percent)	0.4	0.3	0.6*	0.3
THC (ppm)	1800	1800	2000	2000
Temperature (C)	209	158	259	177

*Approximate average based on direct instrument readings only.

MODIFICATION (D)* FIREBRICK PRIMARY AIR DISTRIBUTOR

* Modification (C) Not Shown - Consisted of External Insulation Only



MODIFICATION (F) FIREBRICK IN SECONDARY ZONE

Figure 6. Stove modifications D and F, internal insulation.

The series of tests on the insulated stove was continued using the flow-controlling secondary air distributor system. With this reduced secondary air flow, the excess air in Test 17 ranged only between 275 to 400 percent. There was some reduction in both THC and CO emission factors compared to the noninsulated stoves in Tests 7-10, although there was no evidence of secondary hydrocarbon combustion.

Tests 18 and 19 were conducted using smaller splits of oak (0.4 kg each compared with about 1 kg each in other tests). This wood is indicated by S on Table 1. Test 18 was run using small splits and the reduced and controlled secondary air. In this test the secondary zone temperatures exceeded 425 C for a short time and reached a maximum of 542 C. While this high temperature was accompanied by a short-time increased burn rate between 4.0 and 6.8 kg/hr, the average burn rate for the test was 2.0 kg/hr, and the overall burn rate pattern was similar to Test 17 (which averaged 1.4 kg/hr). In this test, excess air levels were reduced in both the secondary and primary gas samples, with mid-run levels well below 200 percent. Even more significant was a sizable reduction in both CO and THC emissions during this mid-run portion. The primary CO emissions were as low as 50 to 55 g/kg of wood with a corresponding secondary emission of 29 to 33 g/kg of wood, while the THC emissions were 9 to 15 g/kg of wood in the primary effluent with corresponding 3 to 7 g/kg of wood in the secondary effluent. These short-duration emission levels are somewhat lower than those observed in the insulated modification test (17) but unlike the previous results, these emission levels were sustained for a longer period of time, and at reduced excess air levels. The conclusion was that this modification (Test 18) represented a controlled combustion system in which temperatures exceeding 425 C could be achieved temporarily in the secondary zone by (1) controlling the air supply to prevent quenching, (2) insulating the stove to retain heat energy, and (3) improving the fuel surface area/primary air distribution. The stack temperature was significantly higher in the tests with extensive firebox insulation and small splits (370 to 425 C), but using a secondary heat recovery system may reduce some of this heat loss while producing reduced emissions at a controlled burn rate.

In Test 19 small splits and the conventional secondary air supply system were used. The larger effective burning area resulted in emissions higher than those observed with the larger splits in the same stove design (Tests 15 and 16). No evidence of effective secondary hydrocarbon combustion was observed in this test.

INTERNAL SECONDARY CHAMBER INSULATION

Following these tests, the small box stove was modified further. This design (Modification F) attempted to increase further the secondary zone temperature by placing insulating firebrick inside the secondary chamber. The result was a 4-fold increase in average gas velocities with increased mixing in the secondary zone. This design is shown in Figure 6. Graphic results indicate that there were overall reductions in the THC and CO emission factors, but excess air was high and burn rates were variable. The stack and combustion zone temperatures were moderate to low, indicating that

the firebrick alone did not provide significant heat retention. The general reduction of the emission factors for THC and CO in the secondary zone suggests that some improvement in secondary combustion may have occurred from increased mixing or possibly from buffering of any thermal stratification or wall quenching.

DISCUSSION OF RESULTS

The objective of the research program was to evaluate the effects on emission reductions of stove modifications to improve secondary combustion. Many commercially available stoves are designed with a secondary combustion zone and a secondary air system. In actual practice, these systems are often ineffective in providing continuous secondary combustion, especially at low burning rates. The stove design must provide sufficient air along with the thermal energy and mixing necessary to initiate and sustain the combustion process in any secondary combustion zone.

In some designs, the secondary air is preheated and the secondary zone is heated, and the stoves provide a long residence time and ample mixing. With a well distributed primary air supply, the burn is maintained with minimal excess air levels. Secondary combustion then appears to be an effective means of achieving low emissions. In the box stove, the original design provided little air control at low burning rates and essentially no discrete secondary combustion. Combustion was completed in the primary zone at relatively high burn rates. This resulted in low emissions due to the high burn rates, not due to controlled secondary combustion. In order to improve combustion, the stove was modified to (1) control the air distribution, both in quantity and direction, (2) increase the temperatures in the secondary zone, and (3) increase the mixing of the secondary air and combustion gases.

The methods for increasing the temperature include (1) reducing temperature quenching by limiting excess air levels, (2) insulating the stove to retain heat in the combustion zone, (3) improving the primary combustion rate by increasing the wood surface area and providing suitable air distribution, or (4) preheating the secondary combustion air. The first three of these four modifications were specifically implemented in this program. The fourth approach was partially accomplished in the distributed secondary air system, since the air distributor was in the heated zone.

The results of temperature measurements for the modifications are shown in Figure 7. The temperature range and average for the primary zone gas samples are shown by bar graph. The test numbers correspond to the assigned numbers for each test burn.

The observations based on temperature considerations indicate:

- The controlled secondary air system provided higher temperatures than the conventional secondary air system.
- The amount of secondary air required is relatively low, and larger amounts had insignificant or adverse effects.

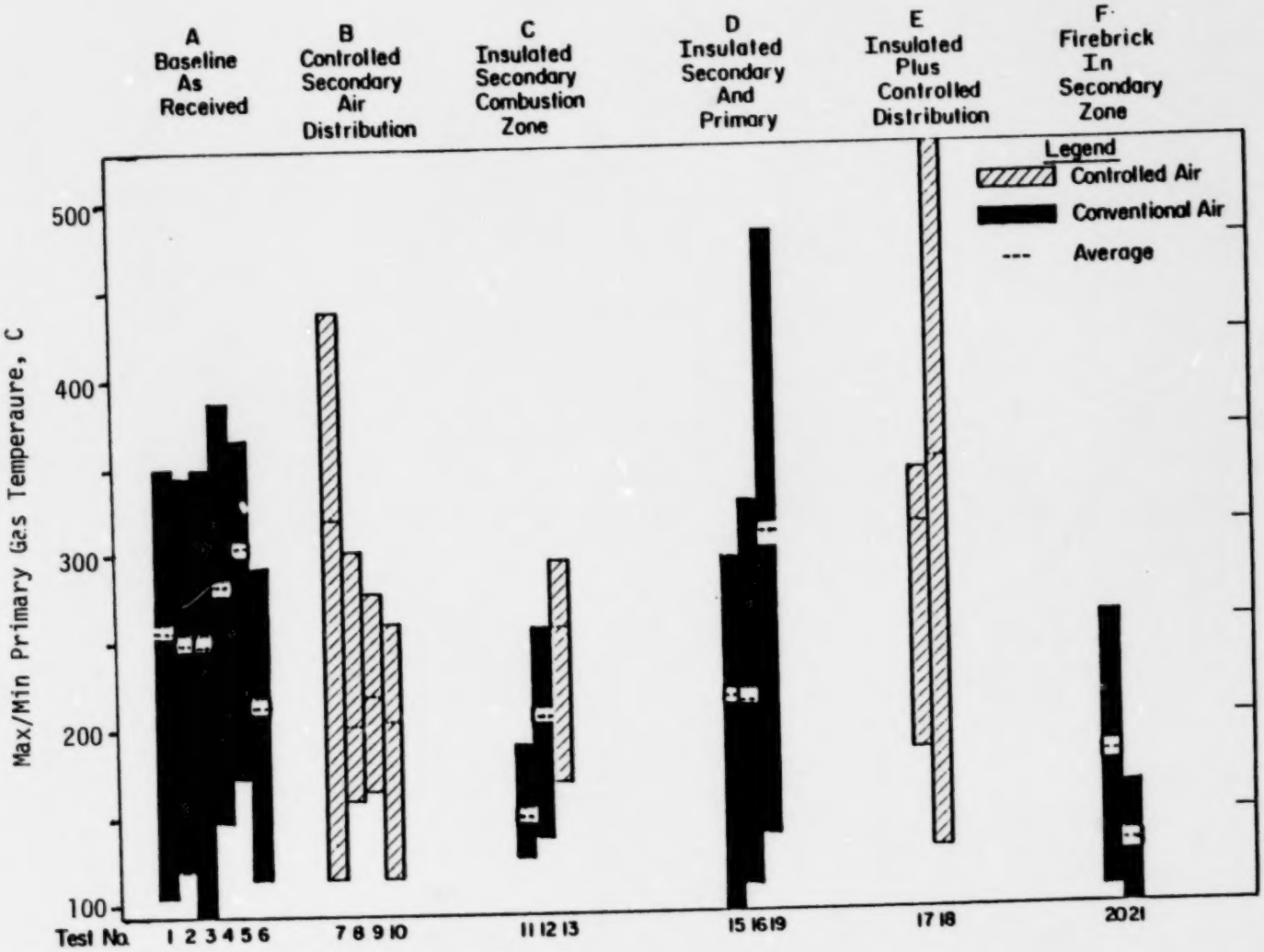


Figure 7. Wood stove combustion gas temperatures.

- Using small splits of wood (0.4 kg) and updraft primary air produced higher temperatures than larger splits with conventional side draft, mostly due to higher burning rates.
- The effect of insulation was minimal unless accompanied by a reduced secondary air supply.

The average THC and CO concentrations for the primary and secondary emissions from 20 box stove tests have been plotted in Figure 8. The graph shows a general reduction of CO in the secondary combustion chamber as indicated by the leftward shift of data. The THC concentrations shows little downward shift. The overall correlation of THC/CO is about 0.5, which agrees with the values previously determined for other stoves under various conditions. (4)

The data in Figure 8 represent concentrations which are not necessarily indicative of actual secondary combustion. To monitor the combustion process, the emission concentrations were converted to emission factors, i.e., g THC or CO per kg of dry wood burned. These factors have been plotted using a graphic program; comparisons of primary and secondary zone emission factors were made visually. As expected, the emission factors show a wide variation, with high initial values that rapidly decline. Sometimes there was a subsequent burn spike (20 to 30 minutes into a burn) followed by generally lower secondary burning rates. The spike indicated the occurrence of a temporary period of effective secondary burning.

The initiation of secondary combustion was assumed to cause a rapid decline in THC and CO emission factors. The difference between primary and secondary emission factors indicated the degree of combustion, and the duration of low levels indicated sustained combustion. Low levels of excess air (EA) contributed to complete combustion by providing low levels of dilution and quenching.

Based on the averaged values of THC and CO emissions for each test, the following observations were made. The average CO emissions from the controlled and limited secondary air tests (Modification B) were the highest of all the group tests, but the overall percent CO reduction in the secondary combustion chamber was also the highest (reductions ranged from 18 and 36 percent). All of the test runs showed a reduction of average CO emissions in the secondary chamber, but the extent of insulation made little difference, i.e., secondary chamber insulation only (C) compared to both primary and secondary chamber insulation (D).

The controlled and limited secondary air tests (B) produced the highest THC emissions, and 3 of the 4 tests showed that reductions in average THC emissions occurred in the secondary chamber. Two other tests that showed reduction in THC emissions within the secondary chamber were the modifications with firebrick in the secondary combustion zone. The results for one of the tests are shown graphically in Figure 9.

The baseline tests with the unmodified stove showed both low average CO and low average THC emissions at high burn rates. It should be noted that in Tests 5 and 6 the secondary zone was bypassed, that is, the internal damper

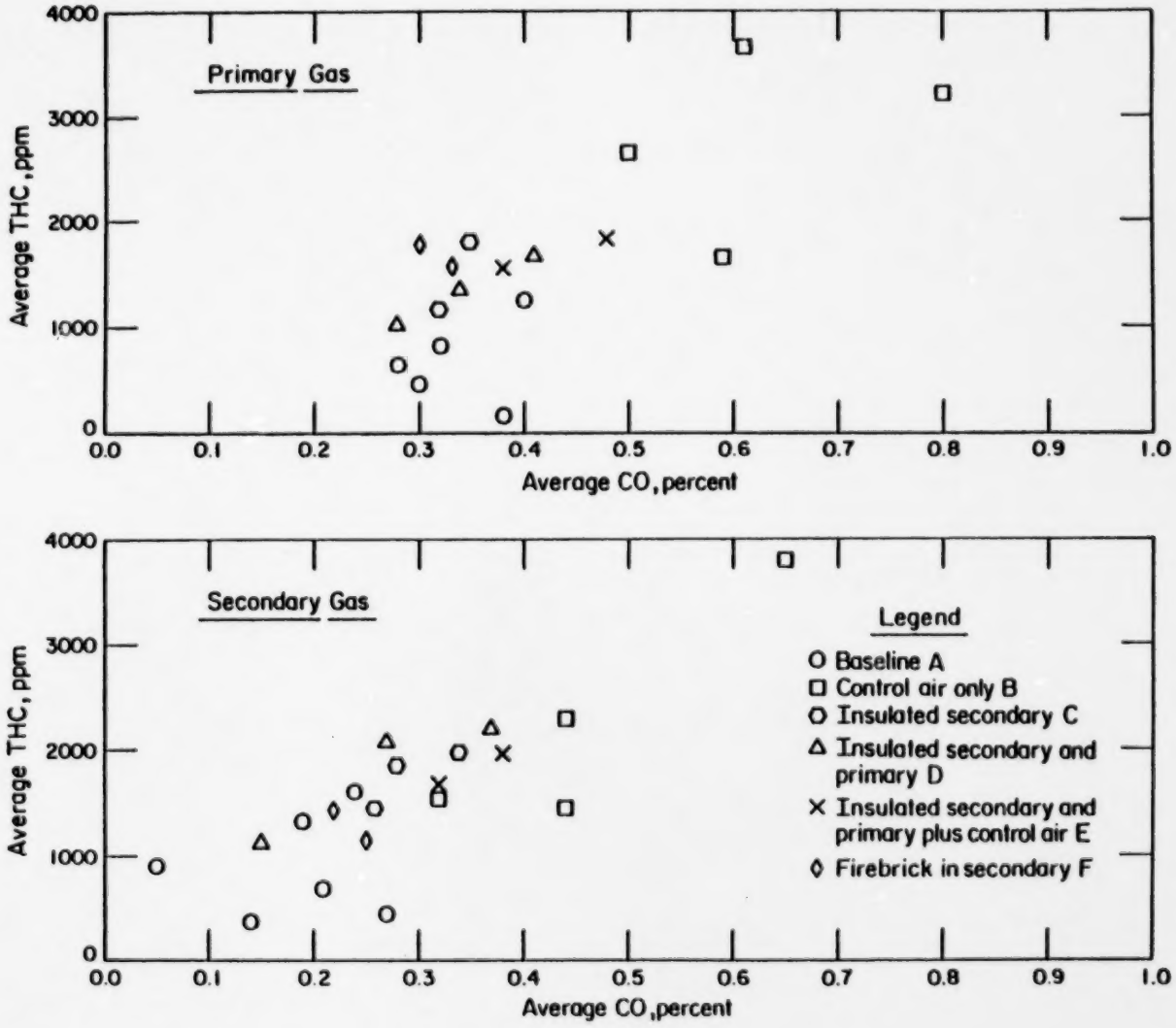


Figure 8. THC and CO concentrations in wood stove combustion gases.

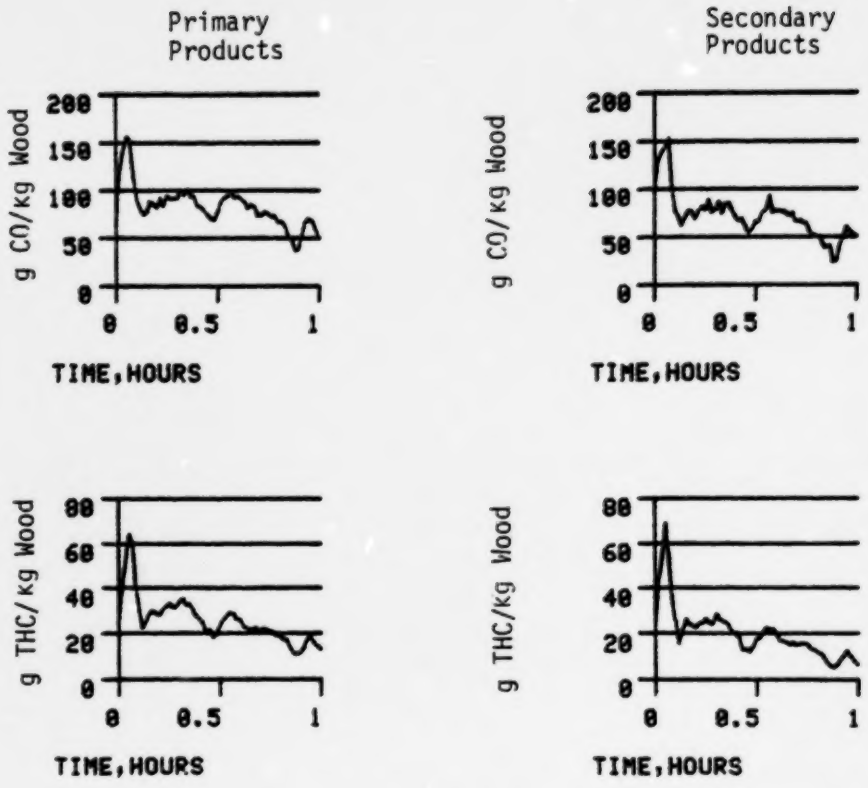


Figure 9. Emission factors, Nordic stove, Test 10.

in the baffle was open, and the secondary air vent in the door was closed. These results indicate that the secondary combustion zone had negligible effects on the stove operation. Thus, the low emissions can be attributed principally to the primary zone combustion characteristics and the extensive air leakage into the unsealed stove.

The tests with smaller pieces of wood did not show any difference from tests with the larger pieces when the average emissions for CO and THC were compared. These tests did indicate that significant short duration reductions could be achieved at higher tempertures.

By visual comparisons of the graphic data and by examination of the actual monitoring system readouts, the various tests were scanned for sustained low emission factors of THC and CO during the tests. The results are presented in Table 4. The table indicates that in all but one case, controlled secondary air was required to maintain low emission factors. The exception was Test 19, in which small splits of wood with the simulated updraft burning were used to improve the wood surface/combustion air distribution.

The "low parameter values" used in this table were arbitrarily selected for these tests, based on observed results. If the definition of completeness of burning from Thornton et al, (3) is used, then the <3 percent C as CO parameter value would be 35 g CO/kg of wood (based on 50 percent C in wood). This more restrictive value was achieved in Test 18 (low value of 28 g CO/kg of wood) for a short time, but was not observed in the other tests. For THC, the value according to Thornton, et al, would be 3.3 g THC/kg of wood representing <0.5 percent C as THC. Only Tests 18 and 7 exhibited THC levels near this value and only for a very limited time. The lowest observed value for Test 18 was 5 g THC/kg of wood; for Test 7 the lowest observed value was 6 g THC/kg of wood.

TABLE 4. TEST OBSERVATIONS SUMMARY

Tests during which emission factors were below arbitrary low parameter values for an extended period of time (∿ 10 minutes)*

Test Parameters	Test Numbers: Primary Carbon Dioxide	Primary Total Hydrocarbon	Primary Excess Air	Secondary Carbon Dioxide	Secondary Total Hydrocarbon	Secondary Excess Air	Test Design Descriptions
	7	7	7	7	7	7	Controlled air, moderate burn rate, secondary flow ∿ 40 g/hr
						9	Same as 7, secondary ∿ 77 g/hr
	10			10	10		Same as 7, secondary ∿ 68 g/hr
	15			15	15		Insulated primary and secondary zone, high burn rate
				17			Controlled air--high primary air, low 45 g/hr secondary, insulated primary and secondary zones
	18	18	18	18	18	18	Insulated primary and secondary zone, controlled air--low primary, low secondary, small pieces wood
				19	19		Same as 18 except no secondary control system
Low Parameter	< 100 g/kg wood	< 25 g/kg wood	< 200 percent	< 100 g/kg wood	< 25 k/kg wood	< 200 percent	

* These values are approximate and are determined primarily by visual comparison of graphic data. Background tests are excluded in this comparison.

SECTION 5

LARGE STOVE TESTS: EFFECTS OF OPERATION TECHNIQUES

The Defiant side-draft stove in previous testing achieved very distinct and effective secondary combustion at high burning rates (i.e., 9 kg/hr). (1) This stove design incorporates several features which promote secondary combustion. More than a ten-fold reduction in CO and hydrocarbon concentrations in the flue gas was obtained with active secondary burning at the high burning rates.

Lower burning rates, which are more typical of residential use, were used in this current program. Changes in the air control settings on the unaltered stove were made to determine their effects at these lower burning rates. Distinct secondary burning was not easily identified, either by gas analysis or by gas temperature readings. Several test runs using thoroughly dried split oak were conducted with the Defiant stove. As in the small box stove, gas samples were withdrawn for analysis and gas temperatures were measured at the outlet of the primary burning zone (before mixing with secondary air) and at the outlet of the secondary burning zone. Results of these tests are presented in Table 5 and Figures 10 through 15. The reported emission factor data in Table 5 are averages of machine-calculated factors obtained each minute during test operation. In each test approximately 4.5 kg of fuel were added to a bed of glowing coals. This was a small charge for the stove size. Immediately after charging, the data collection began and continued for approximately 1-1/4 hours until the test charge was reduced to coals. In these tests the fuel was not completely burned, because at these low burning rates, the time required for complete burning was not distinctly identified, resulting in erratic average burning rate and emission factor calculations.

The first four tests were operated with similar settings of the air-flow controls and in the same manner, except for Test 2, in which more pieces of smaller wood were fired. The emission factors, were consistently reduced by the continued burning in the secondary combustion zone. However, the reductions were relatively small and the emission factors varied considerably. Using smaller pieces of wood (Test 2) resulted in higher burning temperatures and correspondingly lower hydrocarbon emission factors, but the differences were small.

In Tests 5 and 6 the secondary and primary air flow controls were closed, respectively. Leakage air was available in both cases, because neither flow control system was air-tight. With the secondary air supply damper shut, the primary combustion products were relatively hot, and the hydrocarbon emissions were relatively low. When the primary air supply damper was shut, the primary combustion product temperatures were lower, and

TABLE 5. EMISSION FACTOR AVERAGES FOR DIFFERENT AIR SUPPLY CONTROL SETTINGS

Test No.	Dry Wood Burn Rate, kg/hr	Air Supply*		Average Emission Factors, g/kg Wood Burned			
				Carbon Monoxide		Total Hydrocarbons	
		Primary	Secondary	Primary Zone	Secondary Zone	Primary Zone	Secondary Zone
1	2.9	1/3	Full	147	82	43	13
2	1.8	1/3	Full	144	71	25	14
3	2.5	1/4	Full	165	116	48	40
4	2.0	1/3	Full	167	135	41	31
5	2.5	1/3	0	153	114	21	13
6	2.0	0	Full	171	122	75	53

*Fraction of full open damper

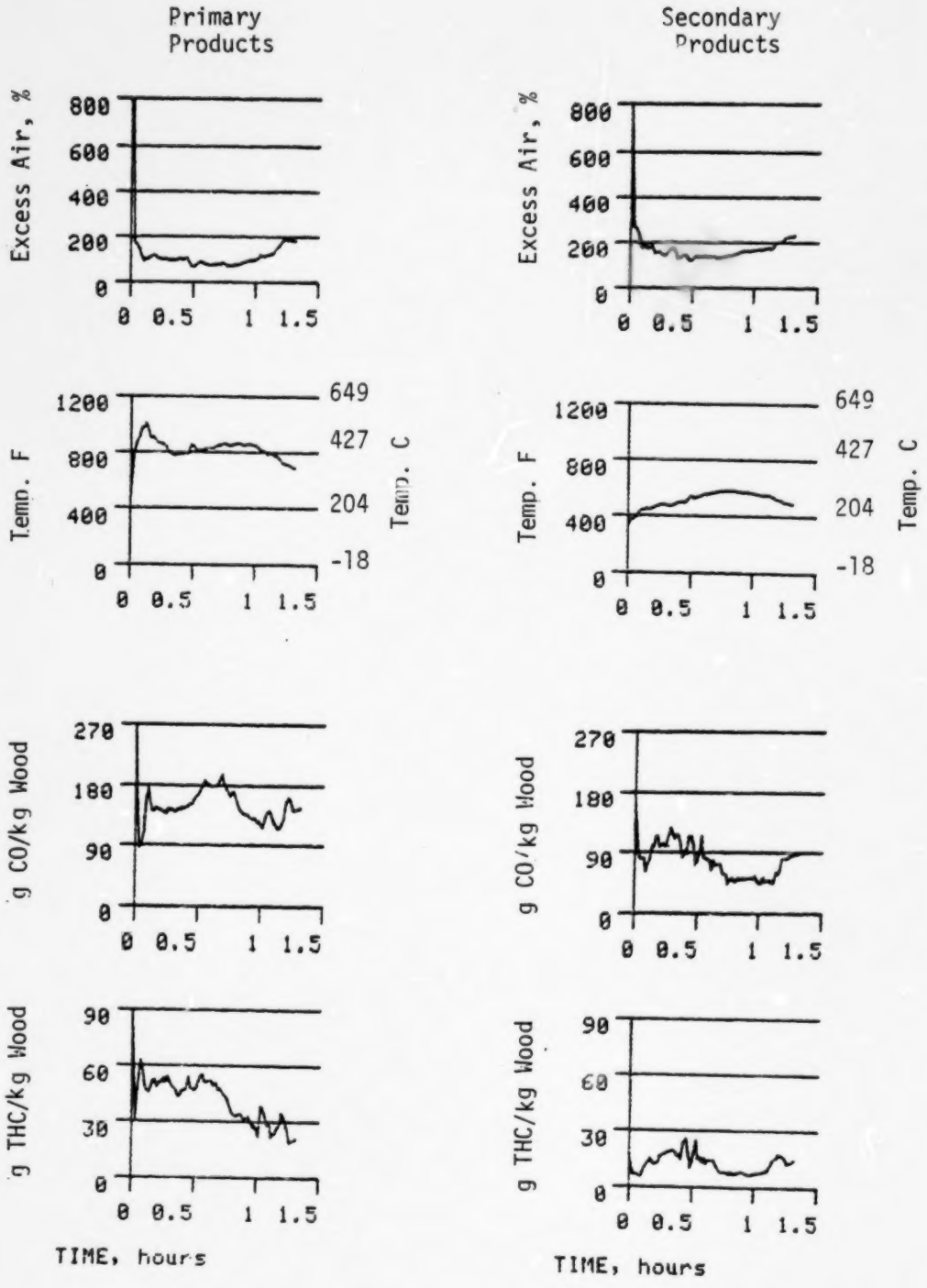


Figure 10. Defiant stove, Test 1, burning large pieces of wood.

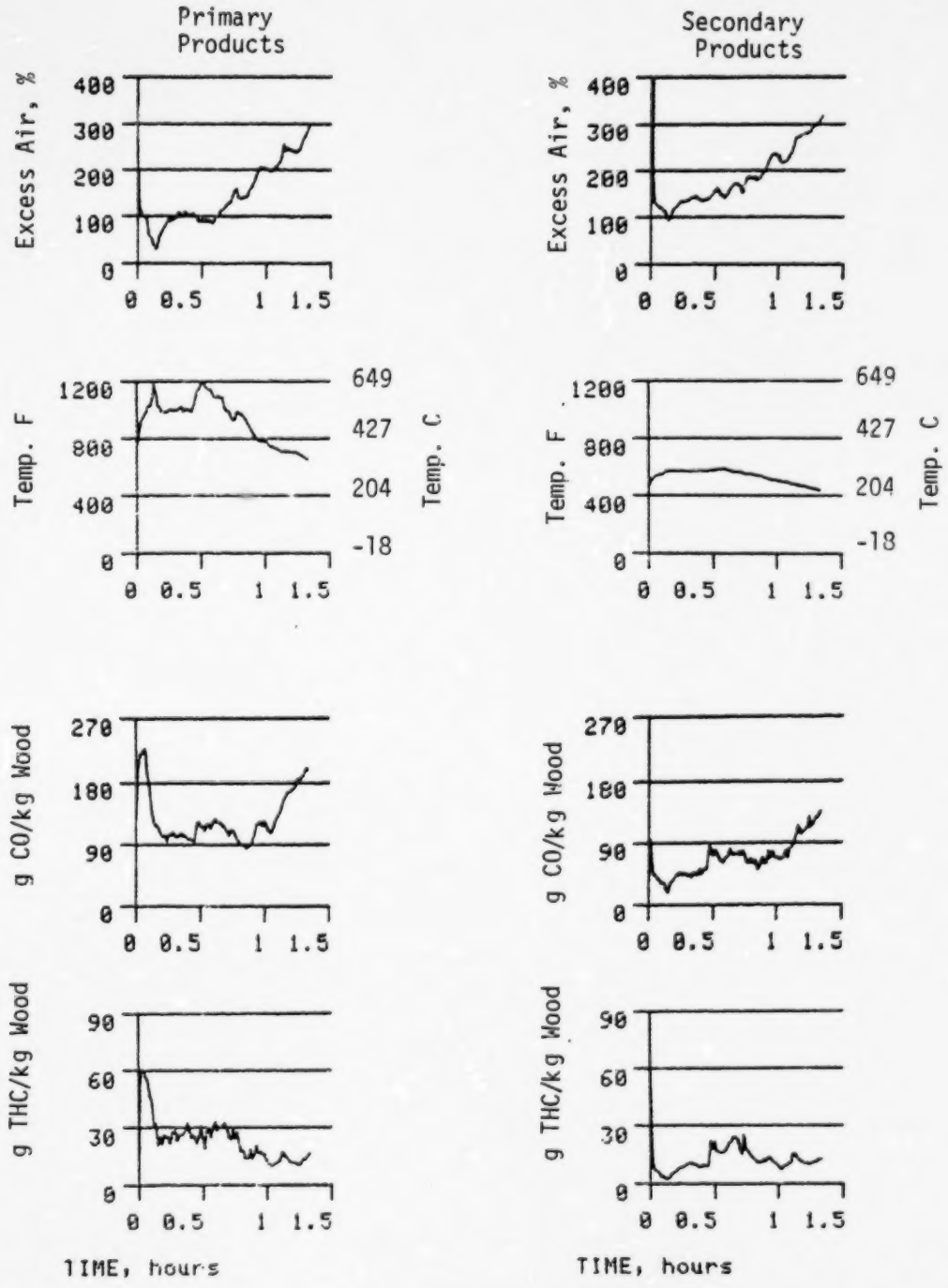


Figure 11. Defiant stove, Test 2, burning smaller pieces of wood.

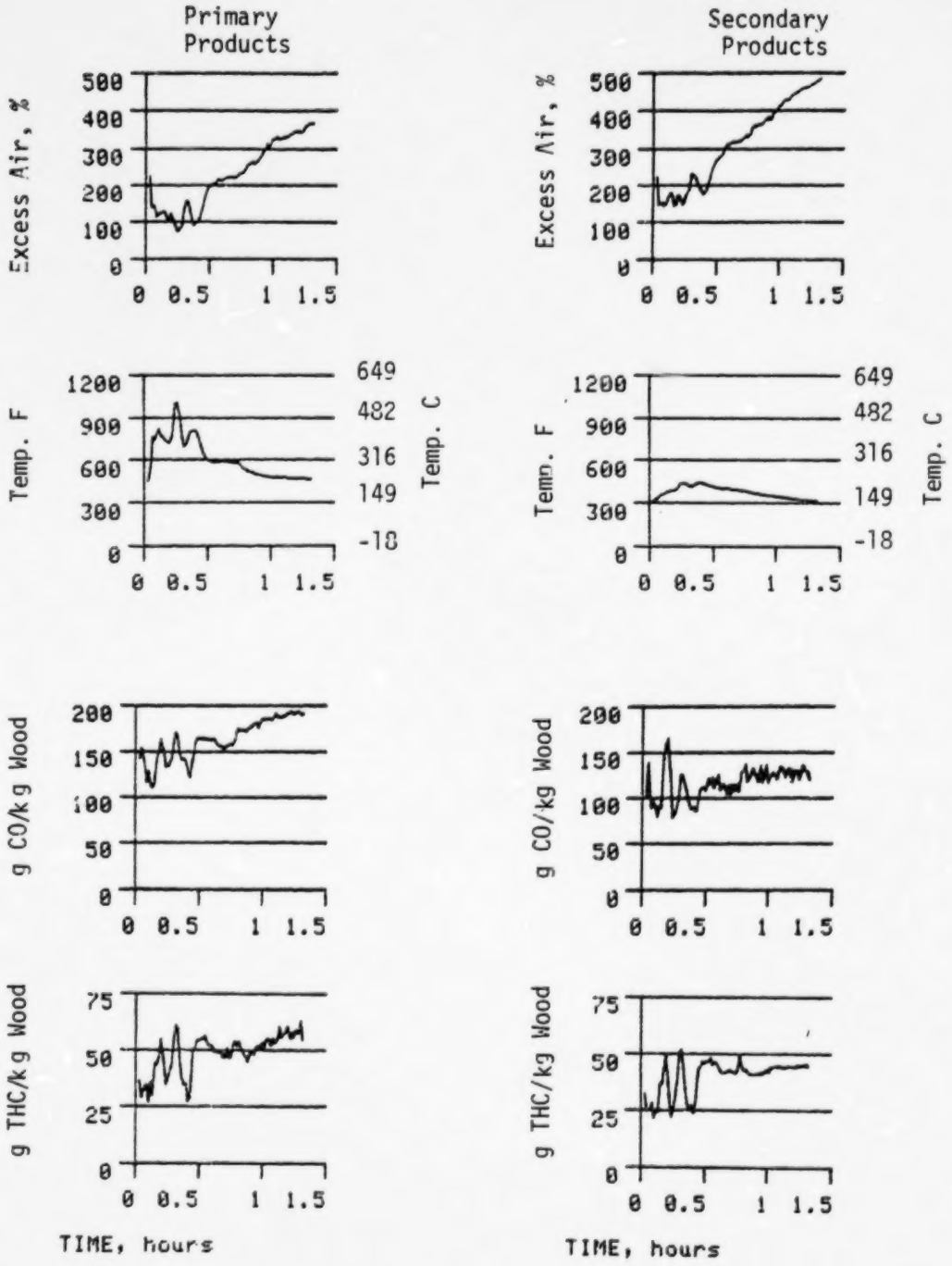


Figure 12. Defiant stove, Test 3, restricted primary air supply.

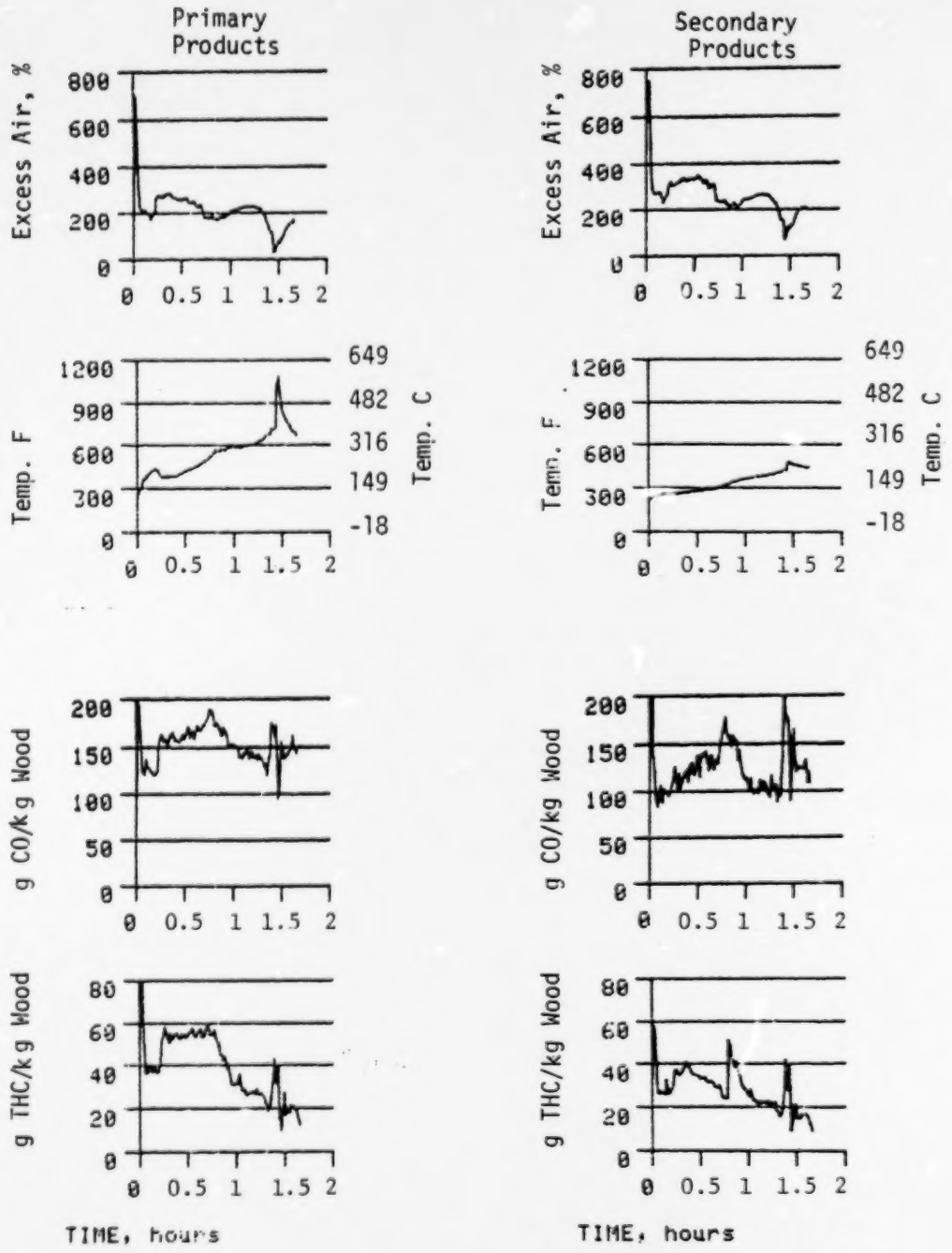


Figure 13. Defiant stove, Test 4, normal primary air supply.

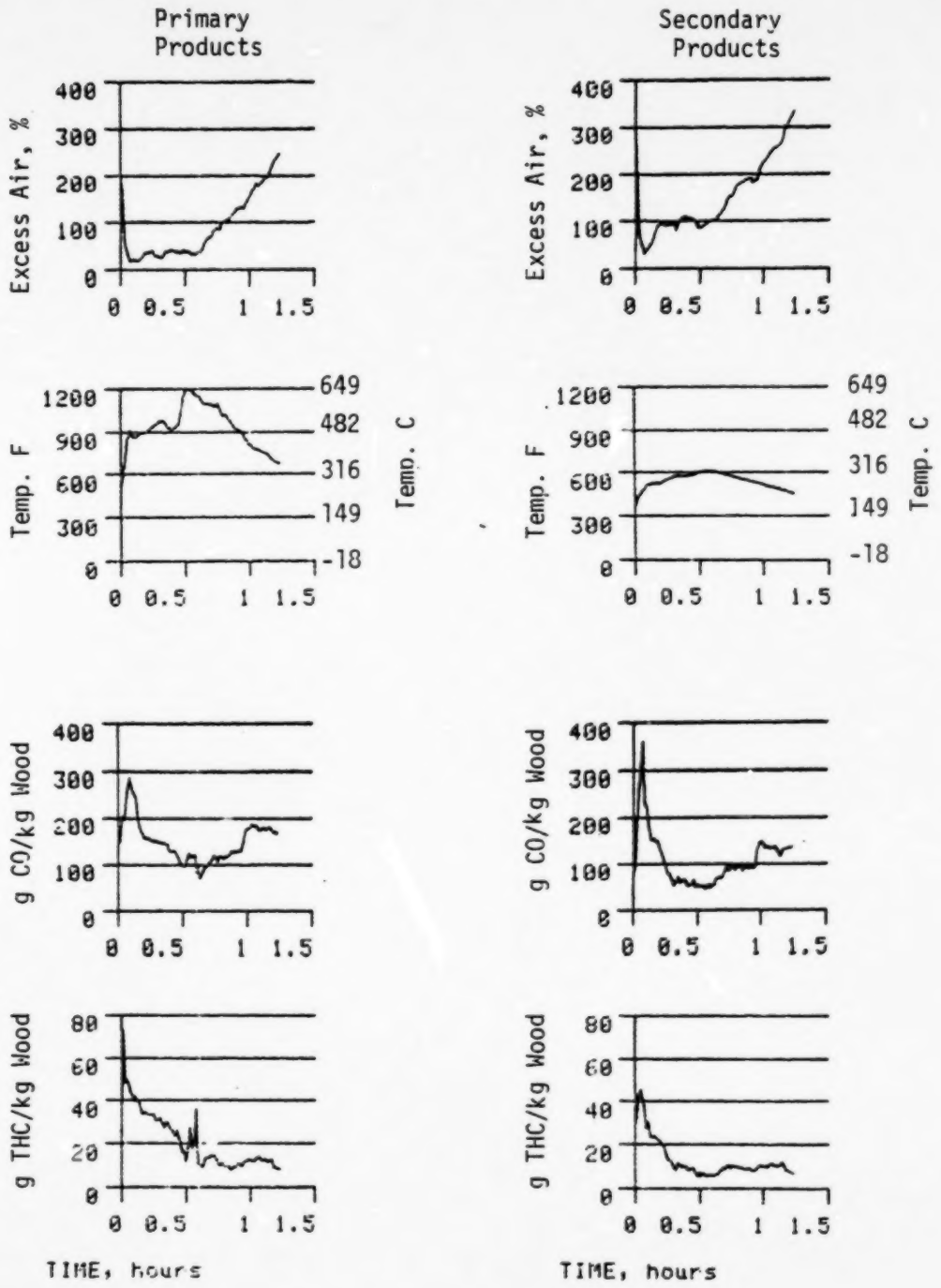


Figure 14. Defiant stove, Test 5, secondary air supply closed.

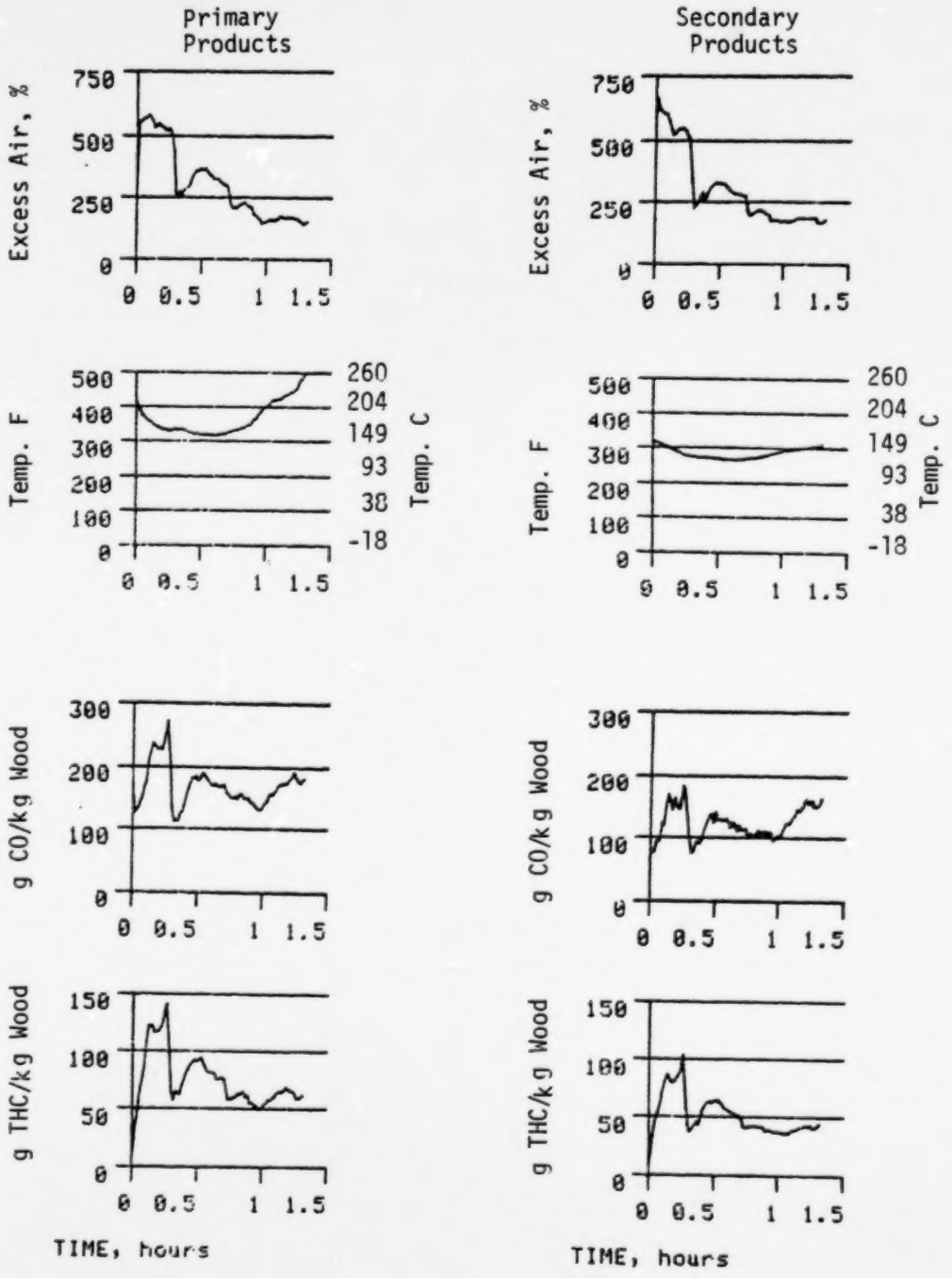


Figure 15. Defiant stove, Test 6, primary air supply closed.

the hydrocarbon emissions were significantly higher. In neither extreme of air distribution was there a large effect on emission factors which could be related to effective secondary burning in the secondary combustion zone.

As in the smaller box stove, the low gas temperatures associated with low burning rates apparently precluded complete burning of the flue gases. In this larger stove, effective distribution of heated secondary air by tuyeres does not result in large-scale reductions in emission factors at low burning rates.

SECTION 6

ADVANCED STOVE DESIGN TO OPTIMIZE SECONDARY COMBUSTION

The Tennessee Valley Authority (TVA) has recently conducted tests on several wood stoves incorporating advanced technologies for efficient and clean burning of wood. (5) A new European-built stove evaluated in that program is designed to optimize non-catalytic secondary combustion. This advanced stove design introduces the heated secondary air through several small holes into the primary combustion products as they leave the primary combustion chamber through a ceramic-lined passageway. TVA found that this design provided equal or higher combustion efficiency compared to a typical air-tight stove at medium and high burning rates (above 2.5 kg/hr). This is not as high an efficiency as that obtained with a catalytic stove. (5) Emission factors for CO, particulates, and polycyclic aromatic hydrocarbons were found to be lower than for the conventional air-tight stove. However, the advanced secondary combustion stove required more operator attention to maintain the effective secondary combustion at the medium burning rates. Effective secondary combustion in the stove could not be obtained at low burning rates, so the stove was not tested at the low rates.

TVA's observations of effective secondary combustion at high burning rates, but not at low burning rates, are in agreement with observations from this program and those from a previous Battelle study. (1)

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